Computational study on neutral beam injection into a Field-Reversed Configuration

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Outline

◆ **Beam ion orbit calculation**
  • Loss mechanism of beam ions
  • Power deposition profile
  • Effect of neutral gas in edge region

◆ **Hybrid simulation for beam injected FRC**
  • Model description
  • Preliminary simulation result
NBI experiment (FIX device)

By the experiment on the FIX, we have found

- Improvement of confinement
- Electron heating

By courtesy of Dr. Inomoto

The NBI prolonged the plasma lifetime significantly. The NB effect was observed just after the translation completion, therefore the NB may cause some changes on the FRC plasma during the translation.
The NB-injected FRCs have $T_e$ of about 10–20 eV higher than the standard FRCs.

- This temperature increment was observed just before the translation was completed ($t=150\mu\text{sec}$).
  $\leftarrow$ The beam power may be absorbed more efficiently during the translation phase.

- The electrons are heated significantly at inner region ($r/r_s=0.5$) and around the separatrix.
  $\leftarrow$ The beam power deposition may be localized according to the distribution function of the high energy beam ions.

$\rightarrow$ A calculation of particle trajectory and a direct measurement of high energy particles are required.

By courtesy of Dr. Inomoto
ARTEMIS
Conceptual D-³He/FRC fusion reactor

An NB is injected tangentially.

Since the confinement region is designed to confine a fusion proton, a neutral beam injected fast ion is also trapped.
Computational study in Gunma University

Interests

- Beam ions are trapped long enough to heat the plasma?
- Is NBI effective to drive the plasma current?
- How is the global motion? How does it occur?

Neutral beam injection into FRCs

- Beam ion orbit calculation
  

- Global behavior of beam injected FRCs
  Ion particle + Electron fluid hybrid code
Analytical model

A neutral beam is ionized by

Charge exchange + direct ionization

Monte-Carlo method

Numerical integration of equation of motion

\[ m \frac{dv}{dt} = q(v \times B) - m v \cdot v \]

Equilibrium state \( \mapsto \) Grad-Shafranov eq.
Beam ion orbit

Time evolution of the magnetic moment

Rapid change

Conserve well.
Correlation of magnetic moment

Points draw a waving curve

Correlation is still remained

Correlation is disappeared

Fast ions are accessible ergodically in the region which is specified by those energy and effective potential
Accessible Region

Störmer region: \[ H - \frac{(P_\theta - q \psi)^2}{2mr^2} \geq 0 \]

Moving in accessible region ergodically, a fast ion suffers...

End loss

Wall orbit loss

Wall orbit loss can not be suppressed by only the strong mirror field.

necessary to control the beam energy. (It is difficult experimentally...)
Beam ion confinement

- Beam ions are lost gradually.
- The mirror ratio of 8 is the best.
Local power deposition profile

The beam energy = 8 keV

\[ R_\psi = \frac{\psi(r = r_w, z = z_{\text{mir}})}{\psi(r = r_w, z = 0)} \]

- Deposition in the edge is significant
  - Long duration
  - Beam ion focusing
  - Not-low density in edge

- The best deposition
  \[ R_\psi = 6 \]

The beam energy = 8 keV

\[ R_\psi = \frac{\psi(r = r_w, z = z_{\text{mir}})}{\psi(r = r_w, z = 0)} \]

- Deposition in the edge is significant
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- The best deposition
  \[ R_\psi = 6 \]
Power deposition

Total deposition in the confinement region

- Up to 95% deposition power goes to electrons
- Confinement of beam ions is not always improved by stronger mirror field.

Fraction of deposited power

To electrons
Power deposition inside the separatrix

Power deposition inside the separatrix --- 35~45%
Low energy beam is necessary to heat the core of FIX plasma

FIX plasma parameters

\[ B_{\text{ext}} \approx 0.05 \text{ T} \]
\[ T_i \approx 100 \text{ eV} \]
\[ T_e \approx 50 \text{ eV} \]
Effect of neutral gas in the edge

Charge exchange: $H^+ + D_2 \rightarrow H + D_2^+$

Assumption:
- Uniform neutral gas pressure outside the separatrix
- No neutral gas inside the separatrix.
Charge exchange cross-section

Fig. Analytical curve used in our simulation

Database
http://dbshino.nifs.ac.jp

Reaction rate

Particle flux = \( n \nu_r \)
Rate of reaction = \( n \nu_r \sigma \)

The reaction in \( \Delta t \) is
\[ n \nu_r \sigma \Delta t \geq \xi \]
Charge is exchanged
Effect on the deposition power

![Graph showing the relationship between deposition power and gas pressure.]

About 0.01 Pa → decrement is 10%

\[ n_{NG} = \frac{p}{kT} = \frac{1 \times 10^{-2}}{1 \times 10^{-23} \times 300} \approx 0.3 \times 10^{19} \]

\[ \frac{n_{NG}}{n} \approx \frac{0.3 \times 10^{19}}{5.0 \times 10^{19}} \approx 0.06 \]

Low gas pressure

Linear decrease

US-Japan Workshop, Sep. 14th 2004

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Evolution of beam injected plasma

Target and calculation principle

- Evolution of 2-dimensional beam injected FRC-like plasma
- Ion particle and electron fluid hybrid code
- Tangential injection on the midplane
- Slowing down collision (b-e, e-i)
- Heat generation for electrons
Hybrid model

Equation of motion for ions and beam ions (particle)

\[ m_\alpha \frac{dv_\alpha}{dt} = q_\alpha (E + v_\alpha \times B) - m_\alpha v_\alpha (v_\alpha - u_e) \quad \alpha = i, b \]

Fluid equation of motion for Massless electron

\[ -en_e (E + u_e \times B) - \nabla p_e + R_{eb} + R_{ei} = 0 \]

Momentum conservation \[ R_{ab} + R_{ba} = 0 \]

Heat balance equation for electrons

\[ \frac{3}{2} n_e \left[ \frac{\partial T_e}{\partial t} + (u_e \cdot \nabla) T_e \right] + n_e T_e (\nabla \cdot u_e) = Q_{eb} + Q_{ei} \]
Calculation of heat generation for ion

Change of thermal energy density per unit time due to \textit{collision}

\[ Q_{ab} = \iiint \frac{1}{2} m_a v_r^2 \ C_{ab} \ dv \]

To calculate the rate of change of ion pressure

\[ \langle \frac{1}{2} m_a v^2 \rangle = \frac{1}{2} m_a u_a^2 + \langle m_a \mathbf{u}_a \cdot \mathbf{v}_r \rangle + \langle \frac{1}{2} m_a v_r^2 \rangle \]

\[ = \frac{1}{2} m_a u_a^2 + kT_a \] (2-D case)

Thermal energy \( = \) Ensemble kinetic energy - flow energy

Ion heat generation (2-D case)

\[ Q_{\alpha \epsilon} = \frac{n_\alpha kT_\alpha(x_i, y_j, t + \Delta t) - n_\alpha kT_\alpha(x_i, y_j, t)}{\Delta t} \]

\( \alpha = i, b \)
Heat generation $Q$ (fluid)

Energy conservation

$$\iiint \frac{1}{2} m_a v^2 C_{ab} \, dv + \iiint \frac{1}{2} m_b v^2 C_{ba} \, dv = 0$$

$$\mathbf{v} = \mathbf{u}_a + \mathbf{v}_r$$

$\mathbf{v}_r$ : random velocity

$\mathbf{u}_a$ : flow velocity

$$\iiint \frac{1}{2} m_a u_a^2 C_{ab} \, dv + \iiint m_a \mathbf{u}_a \cdot \mathbf{v}_r C_{ab} \, dv + \iiint \frac{1}{2} m_a v_r^2 C_{ab} \, dv$$

$$= 0 + \iiint \frac{1}{2} m_b u_b^2 C_{ba} \, dv + \iiint m_b \mathbf{u}_b \cdot \mathbf{v}_r C_{ba} \, dv + \iiint \frac{1}{2} m_b v_r^2 C_{ba} \, dv = 0$$

$$Q_{ab} + Q_{ba} + \mathbf{u}_a \cdot \mathbf{R}_{ab} + \mathbf{u}_b \cdot \mathbf{R}_{ba} = 0$$

From the momentum conservation

$$Q_{ab} + Q_{ba} + (\mathbf{u}_a - \mathbf{u}_b) \cdot \mathbf{R}_{ab} = 0$$

$\mathbf{R}_{ab}$ definition

$Q_{ab} = \iiint \frac{1}{2} m_a v_r^2 C_{ab} \, dv$

$R_{ab} = \iiint m_a \mathbf{v} C_{ab} \, dv$

→Heat generation term for electron
Hybrid Model

Faraday's law
\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \]

Ampere's law
\[ \mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B} \]

Quasi-neutrality
\[ n_e = Z_i n_i + n_b \]

Current density
\[ \mathbf{j} = Z_i e n_i \mathbf{u}_i + e n_b \mathbf{u}_b - e n_e \mathbf{u}_e \]

Initial equilibrium
\[ \mathbf{j}, \mathbf{B}, n_e, T_e, u_e \theta \]

Eq. motion (ion)
\[ n_i, u_i, n_b, u_b \]

Quasi-neutrality
\[ n_e \]

Heat Balance eq.
\[ T_e \]

Fluid equation (electron)
\[ \mathbf{E} \]

El. pressure

All physical quantities at the next time step are determined.
Magnetic field & electron pressure

Magnetic field

0  1.4  2.8  4.2 $\mu$sec

Electron pressure

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Flow, Electric field

$1.4 \mu$sec

$E_r$

$U_{ix}$

$n_1$

$j_\theta$

$U_{er}$

$Q_{ei}$
Discussion

Friction for electrons

Field-null

Separatrix

\[ E = \frac{1}{en_e} (j \times B) \]

Ion rotation

\[ E \times B \]

Electric field (Hall term)

Ion rotates

Electron is dragged

Electric field

\[ E \times B \]

Drift
NB is injected, though…

Magnetic field profile 1.4 µsec after the injection

With NB

No difference can be found

Without NB

Beam current = 20 A
Beam speed = 10 thermal speed

Beam ion impacts wall directly

Beam energy should be decreased
Summary

• Calculation of beam ion orbit
  – NB-injected fast ions exhibit the non-adiabatic motion. Due to this, the beam ion suffers from a wall orbit loss. Target plasma parameter efficient for NBI heating should be investigated.
  – The neutral gas in the edge region is not needed to worry.
Summary

• Hybrid calculation
  – Considering the electron pressure and friction force due to collision, we made the hybrid code to calculate the global motion of NB-injected 2-D FRC.
  – 2-D FRC decays too rapidly. Further investigation is necessary.
  – 3-D FRC will be simulated in a near future.